SEPTEMBER 2021
IB: 21-09-A

STUDY REPORT

Uncaptured Biogenic Emissions of BECCS Fueled by Forestry Feedstocks

Prepared for: Natural Resources Defense Council
Submitted on: 31 August 2021
Hammerschlag LLC document no.: NR-040(g)

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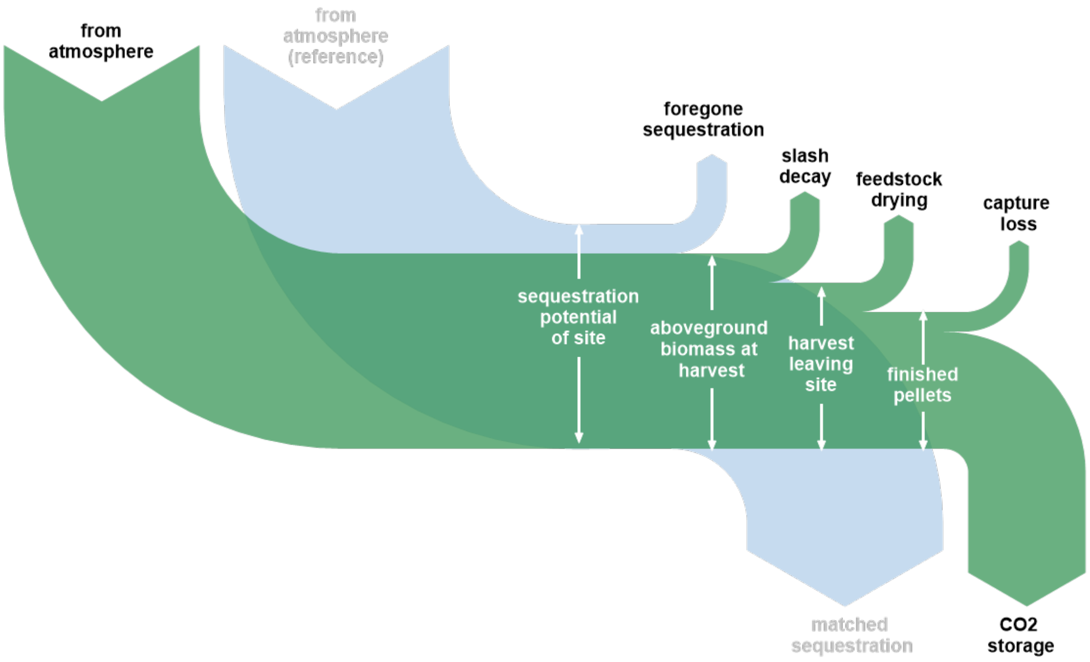
Background

Bioenergy with Carbon Capture and Storage (BECCS) promises capture of the biogenic carbon dioxide (CO_2) from biomass combustion for electric generation. From the perspective of global warming, the simple fact of capturing the biogenic CO_2 is an incomplete picture: what really matters is the net greenhouse gas (GHG) emissions to the atmosphere due to the entire fuel supply chain. This has long been recognized in the literature,[1,2,3,4,5] and while the fossil fuel-related GHGs from trucking, processing and shipping biofuel are easy to comprehend, the net biogenic GHGs evade easy explanation. We attempt to ease description of the biogenic GHG balance by dividing it into four sources: slash decay, feedstock drying, foregone sequestration, and capture loss (Figure 1).

Figure 1 – Carbon mass flow associated with a BECCS power plant (green), and carbon mass flow associated with the same landscape dedicated to biological sequestration (blue). Over the lifetime of the BECCS power plant, green flows are approximately constant, but the blue flows diminish in size as the landscape approaches its carbon carrying capacity.



Slash is shorthand for harvest residues left in the field. In the case of a forest harvest, slash consists of tree tops, branches, and foliage that remain on the ground after logging. These produce GHGs as they decay on the forest floor. **Feedstock drying** is done in part by combusting a portion of the biomass harvest itself for heat, which produces combustion GHGs. **Foregone sequestration** is a lost opportunity for more intensive sequestration. The land dedicated to BECCS feedstock would experience an alternate fate if BECCS were not developed – if that fate draws down more atmospheric carbon than the BECCS feedstock there is foregone sequestration. **Capture loss** is the portion of combustion CO_2 that the chemical or mechanical systems used to extract CO_2 from the exhaust stream are unable to capture.

This memo describes analysis comparing aboveground, biogenic emissions (or sequestration) associated with a BECCS plant, to aboveground, biogenic emissions (or sequestration) associated with a reference case absent the BECCS plant. The BECCS plant is presumed fueled by wood pellets, and presumed to operate at a constant output throughout a 40-year lifetime.

For the sake of simplicity and clarity, we evaluate two feedstock sources supporting the wood pellet manufacture. A **clearcut** case supplies the pellet mill with pulp-grade roundwood from dedicated, even-aged plantation forests; and a **thinning** case supplies the pellet mill with small whole trees thinned from an even-aged plantation forest otherwise dedicated to a non-BECCS purpose. All quantitative analysis is contained in a companion spreadsheet model.[6]

The intent of this study is to provide an estimated range of scale for each of the three biogenic emissions sources, to illustrate the relative contribution each might make to the complete carbon footprint of a BECCS power plant. The ranges of scale are intended to be representative of any wood pellets derived from plantation forestry, but where calculations required physical assumptions we favored parameters representative of loblolly or slash pine grown in the southeastern United States, one of the fastest growing sources of wood pellets.

Slash Decay

In most academic analyses of slash its quantity is estimated not by modeling or measuring the logging process, but rather by modeling the biomass in the crown of the standing tree. The crown consists of the tree top (itself defined as beginning where the stem diameter falls below a given threshold) plus all branches, and is an excellent correlate for the non-merchantable portion of the timber.[7]

Though the values in Table 1 indicate that up to a quarter of aboveground biomass may remain after logging, equipment and practices exist to collect and remove large fractions thereof.[8] Logging slash has critical nutrient value for the soil,[9] so land managers will likely use their best judgment toward removing material useful for drying energy or pellet feedstock while simultaneously leaving a sufficient amount to ensure successful, future harvests.

Table 1 – Fraction of aboveground biomass left as slash after clearcut logging, and associated emissions commitments.

study	species mix	slash as fraction of gross	emissions commitment *tCO_2e/t pellets*
Wade 1969	loblolly pine	11.1%	0.328
Barber & van Lear 1984	loblolly pine	25.9%	0.916
Schnepf et al 2009	mixed conifer	22.3%	0.753
Joint Research Centre 2021	European avg.	20.0%	0.657

Since harvesters do have control over the quantity of slash remaining, and since there will be a genuine tension between utilizing slash for drying energy and leaving it on-site for soil health, I propose that the range of values shown in Table 1 are consistent with 10% to 20% of standing biomass left on-site.

Slash left on-site will decay over the next several decades; the eventual emissions associated with that decay are represented by the *emissions commitment*, the computed total, future emissions after the slash has decayed. In some cases the slash will be burned at the site, which will produce similar emissions as decay, but occurring immediately after harvest rather than over a longer period. Because emissions commitment is integrated over the entire future, it is a characterization that is insensitive to the forester's choice to burn or leave the slash. 10% to 20% of standing biomass left onsite corresponds to an emissions commitment from **0.292 to 0.657 tCO_2e/t pellets** under the assumption that all decay ends in carbon dioxide. Because the BECCS plant fuel demand is presumed constant each year, the quantity of slash created each year is a constant and the computed emissions commitment is as well.[10]

Though tree stumps and roots are often visually prominent in slash fields, they are rarely included in published quantifications of slash, generally due to the merchantability-focused viewpoint of the research's stakeholders, and then specifically due to the habit of estimating slash quantity from the standing tree's crown. The stumps and roots represent a substantial carbon pool and should be considered in future extensions of this work.

Additionally, in wet conditions slash can decay to methane rather than carbon dioxide. Methane is a more potent greenhouse gas than carbon dioxide.

The computations in Table 1 omit stumps and roots, and ignore the potential for methane generation. Both mechanisms would increase the potential for post-harvest GHG emissions from the field, so the values in Table 1 may be considered conservative underestimates of actual slash-related emissions commitment.

Feedstock Drying

At harvest, a loblolly or slash pine bole will have a moisture content between 78% and 128%.[11,12] After harvest the boles, or hogged (chipped) biomass, can be dried to about 50% moisture content with relatively low-energy approaches that make substantial use of ambient air temperature, sunlight, or both. Feedstock for a wood pellet plant, however, must have a moisture content of 12% or less in order to manufacture finished wood pellets with a 7% moisture content.[13]

Drying to moisture contents this low requires more energy-intensive methods, and often the preferred energy source is the biomass itself. In these cases, the drying energy source is usually a mixture of bark and other low-grade feedstock; production grade feedstock; and in the case of sawmills, sawdust. For the purposes of this study, we assume that drying energy of forestry-derived wood pellets induces a proportionate draw on the feedstock biomass.

Publications agree on a heat requirement for evaporating water between 3,500 and 4,000 MJ per metric ton of water,[14,15,16] which is between 1½ and 2 times the theoretical heat of vaporization.[17] However, publications differ greatly on the gross heat energy actually required for drying, ranging from 1,400 to nearly 11,000 MJ per metric ton of pellets.[18]

Table 2 – Published values for heat energy and emissions associated with lumber and pellet feedstock drying. Where there was no published value for GHG emissions, we estimated these based on the reported heat energy and the IPCC default emission factor for wood combustion. "t" means metric ton; "GJ" means gigajoule; "Mbf" means thousand board feet.

	heat energy required for drying		GHG emissions of heat energy	
study	as published	harmonized *MJ/t pellets*	as published	harmonized *tCO_2e/t pellets*
Thek & Obernberger 2004	1021.52 kWh/t pellets	3,677	--	0.412
Bergman & Bowe 2007	5.8 GJ/m^3 lumber	10,346	398 kgCO_2/m^3 lumber	0.710
Uasuf 2010	0.51 t fuel/t pellets	3,947	--	0.442
Hanssen et al 2017	3.96 GJ/t H_2O	1,406	424 kgCO_2e/t pellets	0.424
Ray 2019	--	--	498 kgCO_2/Mbf lumber	0.376

Several sources of drying energy are described in Table 2. One source, Bergman & Bowe 2007, appears to be an outlier. Since it is a high-valued outlier removing it is a conservative choice with respect to characterizing uncaptured biogenic emissions, so we will proceed without the datapoint. This leaves us with a range of drying emissions from **0.376 to 0.442 tCO_2e/t pellets**.

Foregone Sequestration

Simplified Foregone Sequestration: Even-Aged Plantation on a Single Tract

The mass of an equal-aged forest plantation increases with a sigmoid function over time: mass accumulation is slow at first when the saplings are tiny, then it accelerates to a high rate during the plantation's middle age, and finally will slow down if left unharvested to become a mature forest. (Figure 2) For purposes of illustration, our nominal forest growth curve used to illustrate the logic of foregone sequestration is constructed with parameters typical to loblolly pine, a commonly used plantation species in the southeastern United States.

Figure 2 – Chapman-Richards growth curve for a forest exhibiting M_{max} = 118 MgC/ha; τ = 20 yr; and γ = 3.[19] The growth curve shows the total carbon mass of the even-aged forest for the given number of years after planting. Do not confuse this with the rate of growth (which is the derivative of the growth curve, and has a bell shape). See Appendix A for additional discussion of the Chapman-Richards growth curve.

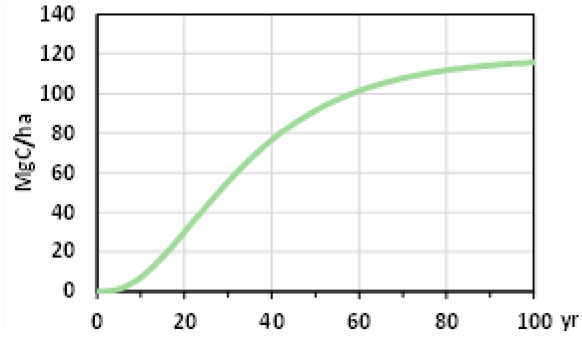
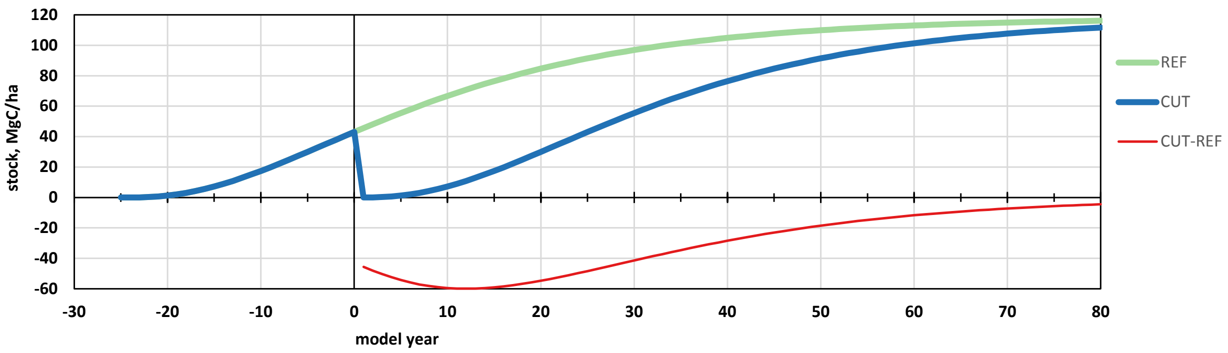


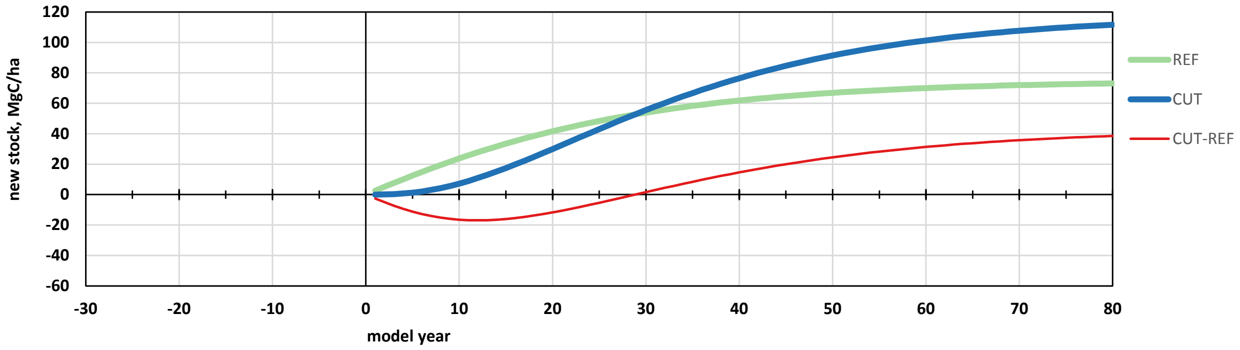
Figure 3 displays the same function plotted for a reference forest planted twenty-five years ago (green), and for a BECCS-case forest that is harvested and replanted at the present (blue). The mass in the replanted forest never equals what would have been achieved in the reference forest, but it eventually becomes indistinguishably close. That is why the red line depicting the difference between the two curves gets closer and closer to zero as time goes on.

Figure 3 – The blue trace shows carbon stock in an even-aged loblolly plantation forest planted 25 years ago, followed by a clearcut harvest and re-planting on January 1 of year 1. The green trace shows how carbon stock would have evolved in the reference case, had the forest not been harvested at all. The thin red line is the difference between the two cases (blue minus green).



The BECCS case we are evaluating is defined to begin on January 1 of model year 1. Before then, the carbon lost to the atmosphere or sequestered are equal for the reference and BECCS cases. We are only interested in comparing the amount of *newly sequestered* carbon after the BECCS-related land use action occurred. This is equivalent to dropping the reference curve down so that it equals zero at year zero, which we have done in Figure 4.

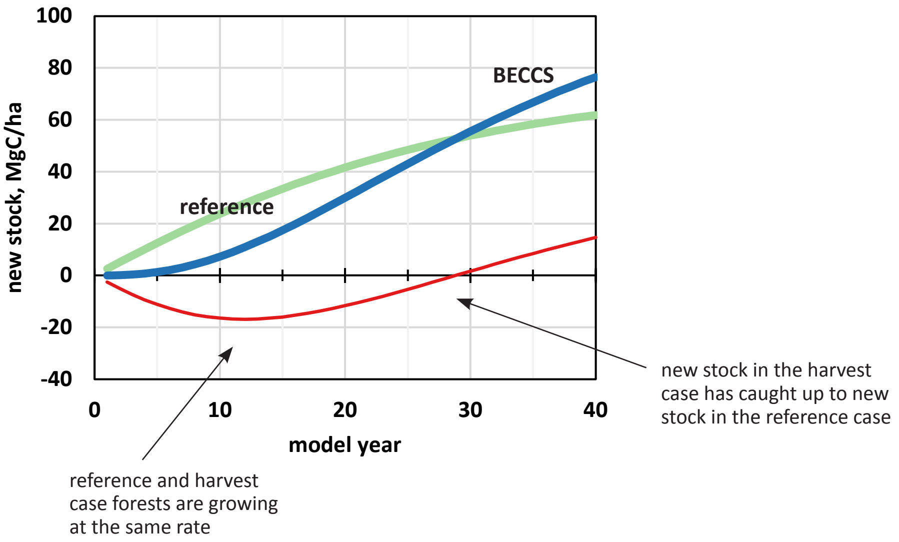
Figure 4 – *New* carbon stock gained after the harvest year.



Now things get more interesting. Left unharvested, the reference forest (green) would have been gaining mass much more quickly than the saplings starting after harvest for BECCS (blue). Eventually, though, the replanted forest reaches its highly productive middle age when the reference forest would be slowing down into maturity, and the replanted forest eventually exceeds the reference forest in *new* stock. In Figure 4, this happens at approximately year 29.

Let's zoom in to the years 1 through 40: from first harvest to the industrial planning horizon associated with the BECCS power plant (Figure 5).

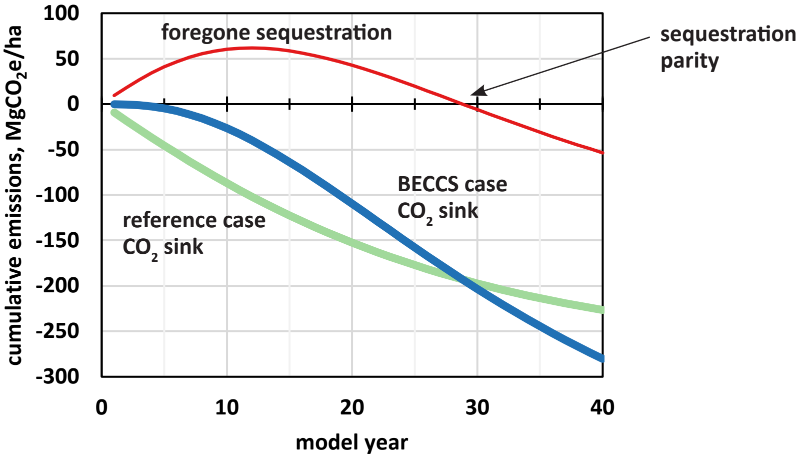
Figure 5 – Identical to Figure 4, but showing only policy-relevant years.



In the first few years after the BECCS-case harvest the new saplings are still growing slowly; the reference forest would have been growing faster and a carbon debt is accrued, shown by the red line dipping below zero. At about age 12 the replanted forest passes up the reference forest in growth rate but then it still takes quite some time for the carbon debt to be repaid: only at year 29 is the replanted forest's mass finally equal to the new growth that would have happened in the reference case.

Finally, to cast the phenomenon from the point of view of the atmosphere and identify foregone sequestration, we simply flip the graph upside down and multiply by the CO_2/C mass ratio, Figure 6.

Figure 6 – CO_2 sinks and foregone sequestration from even-aged plantation clearcutting on a single tract.

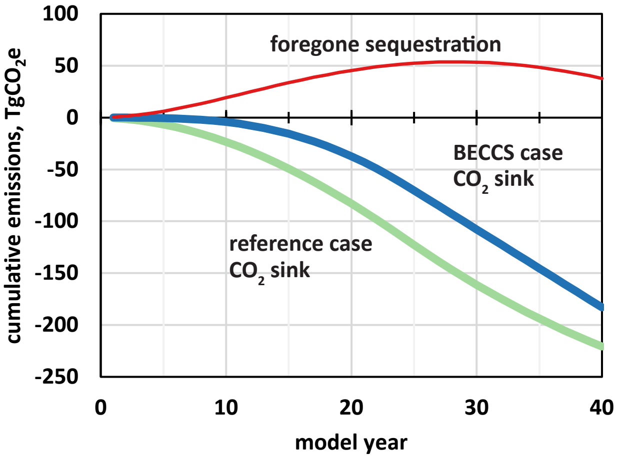


Foregone sequestration becomes zero at year 29, the year in which the carbon debt has been repaid for this tract.

Expanding to the Entire Landscape

A utility-scale BECCS plant will draw biomass from a large number of tracts, each being harvested repeatedly according to the silvicultural rotation length. We simulated this more complex situation for a 25-year rotation,[20] assuming that at each of the 40 years in the analysis, sufficient 25-year-old tracts exist to supply a 500 MW BECCS plant with a net heat rate of 10.2 mmBtu/MWh.[21] The result is shown in Figure 7.

Figure 7 – CO_2 sinks and foregone sequestration from clearcutting of even-aged plantation tracts sufficient to support a 500 MW BECCS plant.



Applying the analysis to an entire landscape delays the achievement of sequestration parity significantly – in fact beyond our model's time horizon. During the first 25 years of the power plant's operation, more and more tracts of forest are being added to the landscape touched by the powerplant's demand, each tract experiencing its largest values of foregone sequestration in the first years after harvest. The landscape has to work (sequester) against an unrelenting tide of newly lost stock, until finally the first-harvested tracts enter their second rotation and the process can stabilize toward eventual sequestration parity.

Relating Foregone Sequestration to Energy Outputs

The quantity of foregone sequestration varies over time, in contrast to slash emissions commitment or feedstock drying each of which can be represented by a fixed, intensive value. Also unlike slash emissions commitment or feedstock drying, foregone sequestration is a cumulative value measured from the project start. In order to generate intensive values of foregone sequestration, pellet consumption must be computed on a cumulative basis as well. Table 3 illustrates the computation of foregone sequestration on an intensive basis, at 10-year intervals after project initiation.

Table 3 – Translation of extensive foregone sequestration to intensive foregone sequestration. The intensive foregone sequestration (last data row of the table) is computed by dividing extensive foregone sequestration (first data row) by pellets required (fourth data row). All values are computed with the BECCS Emissions Simulator modeling a 500 MW BECCS plant with a heat rate of 10.2 mmBtu/MWh . "TgCO$_2$e" means teragrams (million metric tons) CO$_2$ equivalent, "TWh" means terawatt-hours (million megawatt-hours), "EJ" means exajoules.

scenario parameter	units	year 10	year 20	year 30	year 40
foregone sequestration	TgCO$_2$e	15.67	37.22	43.73	30.92
cumulative plant requirements					
electricity production	TWh	43.8	87.6	131.4	175.2
heat input	EJ	0.45	0.90	1.35	1.80
pellets required	Tg	25.4	50.7	76.1	101.5
foregone sequestration	tCO$_2$e/t pellets	0.618	0.734	0.575	0.305

Foregone Sequestration in Forest Thinning

Pellet feedstock can consist of commercial forestry thinnings removed mid-rotation from a plantation dedicated to conventional timber products. In this case, future carbon sequestration by the trees removed is foregone. However, the thinning induces a **release** effect, which is the tendency for remaining trees to grow at a slightly higher rate once uncrowded. The computation of foregone sequestration in the thinning case is considerably more complex than the even-aged clearcut case described above, so the methodology is elaborated in Appendix B.

Both because of the release effect, and because thinning is a less aggressive incursion into growth than clearcutting, forest thinning typically exhibits lower foregone sequestration than clearcutting. Table 4 shows our model results for thinning 15 years into the growth of a 25-year loblolly pine rotation. As with Table 3, these values represent the effect when summed across sufficient landscape to support a 500 MW BECCS plant with thinnings each year.

Table 4 – Foregone sequestration in a thinning case.
Extensive values are in the first data row, and intensive (output-basis) values in the last row.

scenario parameter	units	year 10	year 20	year 30	year 40
foregone sequestration	$TgCO_2e$	23.18	6.90	-5.20	-31.67
cumulative plant requirements					
electricity production	TWh	43.8	87.6	131.4	175.2
heat input	EJ	0.45	0.90	1.35	1.80
pellets required	Tg	25.4	50.7	76.1	101.5
foregone sequestration	tCO_2e/t pellets	0.914	0.136	-0.068	-0.312

The values in Table 4 are computed under the presumption that the entire thinning take is dedicated to BECCS, while the entire clearcut harvest is dedicated to conventional (non-BECCS) forest products. We also assume that the land manager delays commercial harvest until the thinned forest is able to produce the same yield as the unthinned, 25-year rotation.

With these assumptions in place, the foregone sequestration associated with thinning is observed to accelerate quickly in the early years of plant operation, but then decrease quickly later as well. Unlike the clearcut case, thinning does achieve sequestration parity landscape-wide before the model horizon, after about 28 years (see Figure B4). Table 4 reflects this, with foregone sequestration still positive as of model year 20 but negative as of model year 30.

Variability of Foregone Sequestration

Computed foregone sequestration responds to variables from three major sources:

1. Time;
2. Forest growth characteristics; and
3. Reference and BECCS-case management regimes.

The relationship to time is treated explicitly above and in Appendix B, but our analysis is otherwise based on a single forest growth characteristic, and just two BECCS-case management regimes (one each for thinning and clearcutting). Understanding the three-dimensional field of variability in foregone sequestration requires a detailed study of its own, and is beyond the scope of the current work. We believe that the two BECCS cases assessed here are sufficient to illustrate an approximate, expected magnitude of foregone sequestration when biomass is sourced from southeastern U.S. forests.

Capture Loss

Like any technology, carbon capture does not operate theoretically perfectly. There is an overwhelming consensus in literature that both conventional and advanced carbon capture technologies can be presumed to control approximately 90% of the CO_2 in combustion exhaust.[22] That is, 10% of the combustion CO_2 is lost to the atmosphere. Still, some analysts project that capture rates could be engineered as high as 95%, albeit at a substantive financial cost.[23] Consistently with the balance of this study, we examine a range of outcomes conservative with respect to GHG emissions, from 5% to 10% of combustion CO_2 lost to the atmosphere (Table 5).

Table 5 – Estimated CO_2 emissions of combustion uncaptured by current or developing carbon capture technologies.

	min	nominal	max
carbon capture efficiency	95%	92.5%	90%
pellet carbon lost	5%	7.5%	10%
pellet mass that is carbon	-----------	50%	-----------
emissions, tCO_2e/t pellets	0.087	0.127	0.165

The 5% to 10% range results in capture loss emissions from **0.087 to 0.165 tCO_2e/t pellets.**

Discussion and Recommendation

Power Plant Efficiency

For ease of interpretation, we will cast all GHG emissions on an output basis. Doing so requires an estimate of the BECCS power plant heat rate. Data describing efficiency of the very few utility-scale biomass power plants are sparse, but there is no reason to believe biomass plant efficiency should be substantially different from other solid fuel power plants, of which there are thousands fueled with coal. In the United States, the average coal plant heat rate was 10.6 mmBtu/MWh,[24] which corresponds to a thermal efficiency of 32%.[25] The top 10% of coal plants in the U.S. show an average heat rate of 9.08 mmBtu/MWh, or a thermal efficiency of 37.6%.[26] Advances above this level are possible with supercritical and ultra-supercritical water. One comprehensive study of advanced coal plant designs projected a nominal heat rate of 8.9 mmBtu/MWh (38.5% thermal efficiency) for supercritical coal plants, and 7.9 mmBtu/MWh (43.3% thermal efficiency) for ultra-supercritical coal plants.[27]

Regardless of the underlying efficiency of the power plant's prime mover, a certain fraction of the generated energy will be consumed by the carbon capture process. Estimates of the associated energy penalty range widely, from a 15% increase in heat rate up to a 43% increase in heat rate.[28,29,30,31,32,33] Estimates appear evenly distributed throughout this range, so for the sake of this report we will fix the value at the midpoint, 29%.

Applying the nominal, 29% heat rate penalty of carbon capture to the anticipated range of new biomass plant heat rates 9.08 mmBtu/MWh (like high-performing coal plants in the U.S. fleet) to 7.9 mmBtu/MWh (like ultra-supercritical coal plants) yields an adjusted heat rate range from **11.7 mmBtu/MWh to 10.2 mmBtu/MWh**, or 29.1% to 33.6% net thermal efficiency.

Only the impact of *carbon capture* on heat rate is computed in this report. Carbon *storage* induces an additional energy load, primarily dedicated to CO_2 compression. In many cases CO_2 will be transported to a different location via pipeline and injected there utilizing grid electricity or other sources that do not directly induce biogenic emissions from the BECCS plant's feedstock stream. Hence this emissions source is outside the report's system boundary.

Roll-Up and Summary of Results

The uncertainty in BECCS plant heat rate has the impact of amplifying the range of output basis results, relative to the range of input basis results. Both are summarized in Table 6.

Table 6 – Partial emission factors for uncaptured biogenic GHGs associated with BECCS. Output-basis values assume a power plant heat rate of 10.2 mmBtu/MWh at their low end, and 11.7 mmBtu/MWh at their high end.

	input basis		output basis
emissions source	tCO_2e/t pellets	tCO_2e/mmBtu	tCO_2e/MWh
slash decay	0.292 – 0.657	0.0162 – 0.0364	0.165 – 0.427
feedstock drying	0.376 – 0.442	0.0209 – 0.0245	0.212 – 0.287
20-yr foregone sequestration	0.136 – 0.734	0.0075 – 0.0407	0.077 – 0.477
capture loss	0.087 – 0.165	0.0048 – 0.0091	0.049 – 0.107
TOTAL uncaptured biogenic			0.503 – 1.298

The Table 6 ranges for foregone sequestration reflect the thinning case at the low end and the clearcut case at the high end, and are reported as of the BECCS plant being in service for 20 years. Slash emissions commitment and feedstock drying are constant throughout the plant's lifetime and the same at year 20 as any other. All four phenomena, slash decay, feedstock drying, foregone sequestration, and capture loss are of a similar order of magnitude, and sum to make a combined range (as of the plant's 20th year) of 0.50 to 1.30 tCO_2e/MWh.

Communication of results to the public or policymakers may require different presentations. A few such options are provided, for convenience, in Appendix C.

System Boundary Issues

Nonoverlapping Production Phases

Demand for biomass energy for drying, and loss of biomass to slash, both impact estimates of foregone sequestration. Though the three sources of biogenic GHGs interact, they are computed with methodologies that allow separate values for each with no danger of double counting.

Drying Emissions. The model computes biomass demand working "backward," beginning with the heat demand of the BECCS plant, and incrementing the biomass requirement step-by-step as we work upstream in the production process. The model assigns demand for green biomass removed from the landscape, according to the heat demand of the power plant incremented by the heat demand necessary for drying at the pelletizer. If some drying occurs in the field, or in a yard at the pelletizer, the model user simulates this simply by lowering the kiln heat demand. Doing so automatically lowers the demand for green biomass removed from the forest proportionately.

Slash Decay. The user instructs the model to assume a certain fraction of any harvest is left on the ground to decay or burn. As described above, power plant and kiln heat demand combine to specify an amount of green biomass *removed from the forest*. The model increments the demand for total biomass felled above the demand for biomass removed from the forest, according to the fraction specified by the user for decay on the ground.

Foregone Sequestration. Emissions associated with drying and slash decay are computed exclusively according to quantities of *felled* biomass. Foregone sequestration, on the other hand, is computed by comparing the behavior of *living* biomass in the BECCS and reference cases. Hence, foregone sequestration is computed from two carbon pools entirely separate from the third, felled pool ensuring nonoverlapping GHG emissions sources.

Indirect Sequestration & Emissions

Deployment of the BECCS case, though inducing new emissions from slash decay, feedstock drying, and foregone sequestration, may also induce new sequestration. In fact this is accounted for explicitly in the methodology for computing foregone sequestration of thinning in Appendix B. But are there other indirect effects we may be omitting?

Improved Land Management. If land entering the clearcut scenario was previously neglected or degraded, there will be a relative increase in sequestration due to well-managed forest growth after each BECCS harvest. Following the first few years of sapling growth, the plantation forest will likely be sequestering more quickly than the reference case. This effect is not accounted in the discussion above.

Higher Lumber Yields. In the thinning scenario, the release effect could increase the quantity of merchantable lumber available at the end of the ordinary harvest rotation. Our modeling consistently concludes that the release effect is not sufficient to yield more standing biomass at the end of the underlying rotation period. However, standing biomass and merchantable lumber are not the same thing, and it is possible that the release effect results in mature trees that yield more lumber per unit of forest mass. If this effect were to occur then thinning for biomass could provide the co-benefit of reducing the need for lumber production elsewhere.

Afforestation. Our spreadsheet model draws tracts of land into account as they become available for harvest. For example, if we are modeling a clearcut scenario with a 25-year rotation, then the first year sequestration & harvest are accounted on only 1/25 of the total land that will eventually be under rotation, the second year on 2/25 of the total land, and so forth until the full rotation length (25 years) has been reached. This has little consequence if the reference land was already forested, but if it was unforested then the land owner will need to establish forest on each tract up to 25 years *before* its first harvest. The sequestration associated with initial afforestation, if it is occurring, is not modeled.

Indirect Land Use Change. Pulpwood or other medium- to low-grade timber that is favored for pellet manufacture has other uses as well. Depending on market conditions, the dedication of a given forest resource to pellet manufacture may remove it from other products' value chains and cause new land to support those other products instead. In most cases this effect will increase rather than decrease emissions induced by the biofuels policy. Published research on the topic of indirect land use change is substantial and complex, but beyond the scope of this report.

Belowground Processes

Changes in tangible land management have less visible impacts to soil carbon, root systems, and other aspects of the belowground ecosystem. These are significant carbon pools and their changes will have a material impact on the carbon balances of land use decisions. However, the behavior of belowground carbon pools is more difficult to measure and has historically received less study than the aboveground carbon pool represented by merchantable timber. Future extensions of the analysis documented here should include belowground carbon pools, to the extent that their sizes and behavior are known. Some peer-reviewed forest growth models, for example the United States Department of Agriculture Forest Vegetation Simulator, are capable of simulating these carbon pools in addition to aboveground growth.

Non-CO_2 gases

In anaerobic environments, carbon decay favors production of methane (CH_4) rather than CO_2. CH_4 has roughly ten times the global warming effect for the same quantity of decay carbon,[34] so if any portion of the carbon pools considered in the BECCS and reference cases decays anaerobically, this can have a very strong impact on the GHG balance. Wet conditions (rain) can be sufficient to induce partial anaerobic decay, so like belowground processes consideration of anaerobic decay should be included in further extensions to this work.

Exceptions for Biogenic CO_2

At times policymakers will deem certain CO_2 emissions as inconsequential because they are biogenic. However, the atmosphere makes no distinction between CO_2 arising from one source or another – the quantity of radiative forcing is computed from the quantity of CO_2 in the atmosphere regardless of its origin. The reason that biogenic CO_2 emissions sometimes get a pass is because an *assumption* is being made that the landscape sequestration following harvest produces an equal and opposite flux. The work described in this memo is a replacement for that assumption—a quantification of both the emissions associated with harvest, and sequestration associated with regrowth. *None of the emissions described in this analysis can be granted a biogenic pass, because this analysis represents a complete accounting*.

Durability of CCS

Some literature expresses concern about gradual leakage of industrially sequestered CO_2. This study presumes that CCS is permanent. Leakage would cause a fraction of the captured CO_2 to enter the atmosphere anyway, essentially adding a fourth source of uncaptured biogenic emissions. Future work could account for this either by computing it as a fourth source explicitly; or by expressing potential leakage as an uncertainty; or by considering it in a sensitivity analysis.

Implications for BECCS As a Climate Solution

For reference, the stack emissions of a combined-cycle combustion turbine plant burning natural gas at 50% thermal efficiency are 0.36 tCO_2e/MWh; and the U.S. national average grid emission rate is 0.43 tCO_2e/MWh.[35] The output-basis values in Table 6 exceed these benchmarks, showing that when the feedstock is forestry-based wood pellets, BECCS may not always be a climate solution. Furthermore, demand for biomass fuel induced by BECCS has potential to create massive pressures on the landscape (see Appendix D). Policymakers should proceed slowly, and with consultation from climate and forestry scientists, before promoting forestry-based BECCS at significant scales.

Appendix A: BECCS Emissions Simulator

The BECCS Emissions Simulator

The BECCS Emissions Simulator provides its user the ability to model emissions associated with a BECCS plant supplied by a portfolio of up to seven harvest types chosen from:

1. herbaceous crops,
2. short rotation woody crops,
3. clearcut forestry,
4. thinnings from host commercial forestry,
5. logging slash,
6. agricultural waste, and
7. mill waste.

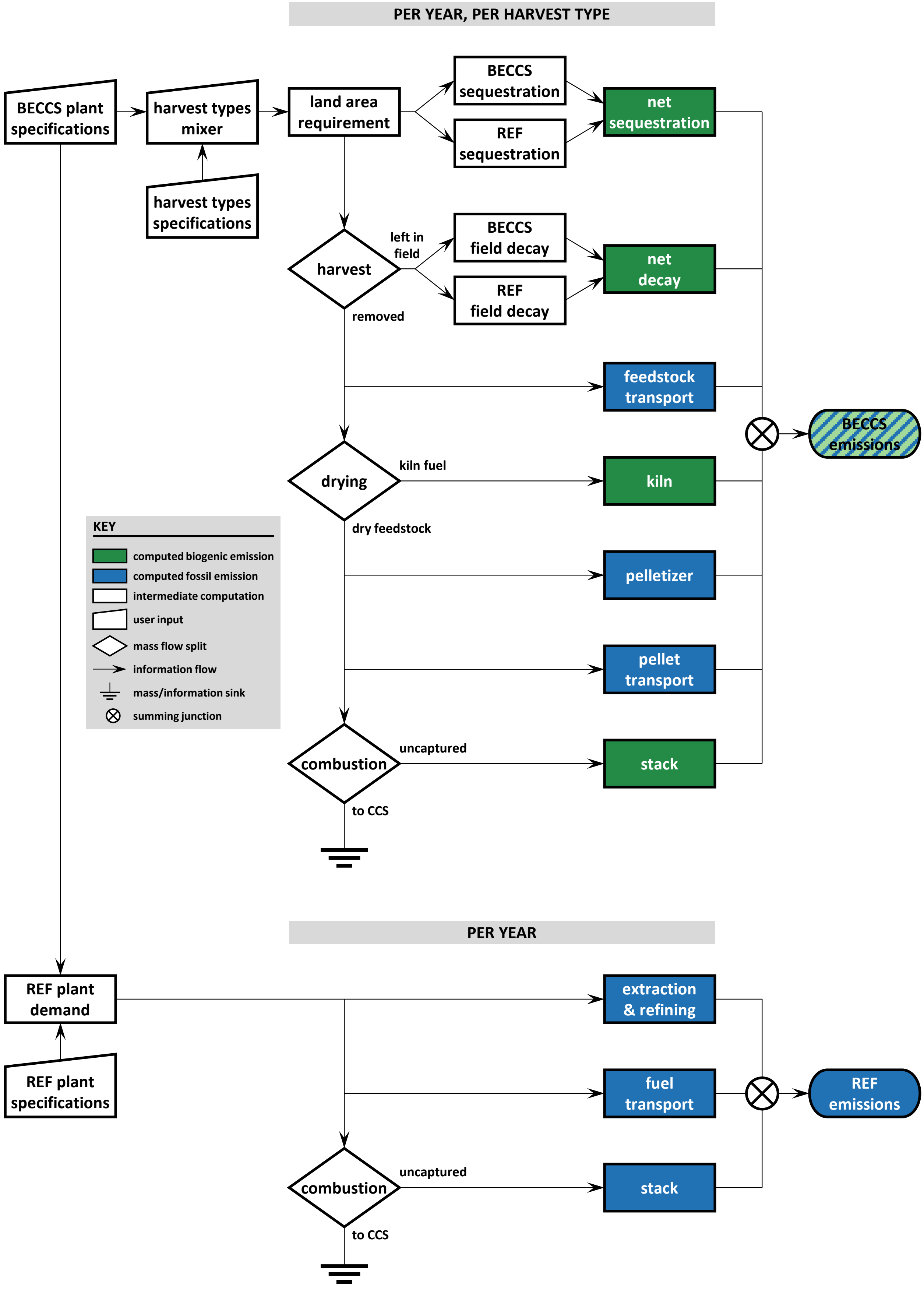
The user can specify multiple parameters defining each harvest type, including fraction of harvest left in field, moisture content, mean distance to pelletizer, weight-% carbon, heating value, and harvest rotation if applicable.

In addition to harvest type specifications, the user also specifies the nature of the BECCS power plant, including nameplate capacity, distance from the pelletizer, capacity factor, thermal efficiency, and rate of carbon capture.

A single comparator case “REF” models a conventional natural gas plant. The user is able to specify the REF case capacity factor, thermal efficiency, and rate of carbon capture. The BECCS Emissions Simulator then sets nameplate capacity automatically to ensure equal generation to the specified BECCS power plant.

The model is coded in Microsoft Excel 2019 and is unlocked, to ensure maximum transparency. A user dashboard provides access to parameters that specify the BECCS power plant, the REF power plant, and the harvest types mixer: a set of seven slider controls that allows the user to allocate feedstock sourcing among them. Specification of the harvest types is split between the user dashboard and dedicated workbook sheets for each harvest type.

Figure A1 – BECCS Emission Simulator information flow.



The BECCS Emissions Simulator information flow shown in Figure represents a single harvest type in a single year. To appreciate the model's full function, it can be helpful to think of the summing junction ⊗ as operating in three dimensions: emission source (shown), harvest type, and model year. The sum will always include all seven harvest types, and will include model years 1 through N, where N is the output year being considered. This latter sum causes the BECCS Emissions Simulator to report cumulative emissions, which is intentional in order to give net sequestration intuitive meaning in the sense of "foregone sequestration" or "augmented sequestration."

Each of the seven harvest types is characterized according to the approaches shown in Table.

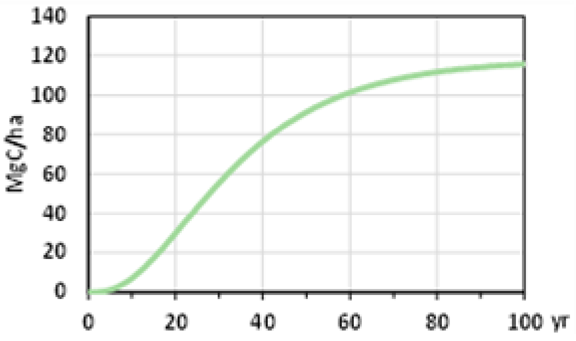
Table A1 – Characterization of the seven harvest types modeled by the BECCS Emission Simulator.

model	BECCS	land use		modeled sequestration mechanisms		modeled field decay	
code	feedstock	BECCS	REF	BECCS	REF	BECCS	REF
HERB	herbaceous crop harvest	herbaceous crop	afforestation	crop growth (annual)	forest growth (continuous)	harvest residue	none
SRWC	woody crop harvest	short rotation woody crop	afforestation	crop growth (rotation)	forest growth (continuous)	harvest residue	none
LOG	pulp-grade timber	clearcut forestry	protected forest	forest growth (rotation)	forest growth (continuous)	harvest residue	none
THIN	silvicultural thinnings	commercial forestry with thinning	commercial forestry without thinning	thinned forest growth (augmented rotation)	unthinned forest growth (rotation)	thinning residue	none
SLASH	scavenged logging slash	commercial forestry	commercial forestry	none	none	unscavenged logging slash	all logging slash
AG	scavenged agricultural field waste	agricultural crops	agricultural crops	none	none	unscavenged agricultural field waste	all agricultural field waste
MILL	industrial biomass waste	not applicable	not applicable	none	none	none	none

Forest Growth Curves

Forest growth needs to be modeled in the BECCS Emissions Simulator in order to compute net sequestration for the HERB, SRWC, LOG and THIN harvest types.[36] The sigmoid functions used (e.g. Figure 1, repeated here for reference) are of the Chapman-Richards type.

Figure A2 (duplicate of Figure 2 in body text) – Chapman-Richards growth curve for a forest exhibiting M_{max} = 118 MgC/ha; τ = 20 yr; and γ = 3. The growth curve shows the total carbon mass of the even-aged forest for the given number of years after planting. Do not confuse this with the rate of growth (which is the derivative of the growth curve, and has a bell shape).



The Chapman-Richards function follows the form:

$$M = M_{max}\left(1 - e^{-t/\tau}\right)^{\gamma}$$

where M_{max} is the maximum mass achieved by the forest, t is time in years, τ is a constant inversely related to the speed of growth also expressed in years, and γ is an empirical, unitless parameter that affects the shape of the curve. This is the function shown in Figure 2, where it is evaluated with parameters scaled to match growth of a southeastern loblolly pine forest.[37] The value of γ was held to 3.0 while the values of M_{max} and τ were fit to minimize the sum of squares between the Chapman-Richards function and the source data. $\gamma = 3$ is at the high end of values typically found in literature, but was chosen in order to suppress early growth and make the concepts related to foregone sequestration more visually apparent. Hence, the calculated, foregone sequestration derived in this analysis can be understood as a maximum.

Due to the merchantability focus of forestry literature, there has been precious little modeling or measurement of early growth. Published growth measurements and models alike were typically executed with a 5-year resolution, and beginning at year 10 or later. Early growth behavior is the critical parameter characterizing foregone sequestration, and accurate quantification thereof will not be possible until early growth is better documented. The Chapman-Richards function was tested in this same academic environment, so its ability to accurately represent early growth is similarly unknown.

Application in this Study Report

The BECCS Emissions Simulator is the primary source of foregone sequestration computations only. Estimates of slash decay and feedstock drying emissions are drawn from peer-reviewed literature. The REF case natural gas plant comparator is unused in this study.

Appendix B: Foregone Sequestration of Thinning

In order to model the impact of thinning on the underlying, Chapman-Richards growth (as described in Appendix A) we apply an **index of suppression** IS as proposed by Hasenauer, Burkhart & Amatels[38] which they attribute to Pienaar[39] and define as

$$IS = \frac{BA_u - BA_t}{BA_u}$$

where BA_u and BA_t are the unthinned and thinned basal areas, respectively. IS is not a metric of flux (annual increment), but rather a time-dependent metric of stock. It is the fraction, at some point in time at or after thinning, of baseline basal area that is lost due to the thin. Pienaar postulated that IS evolves over time according to the form

$$IS_{t2} = {IS_{t1}}^{\beta_1} e^{-\beta_2(t_2 - t_1)}$$

and fit field data to determine $\beta_1 = 0.77$ and $\beta_2 = 0.103\ \mathrm{yr}^{-1}$ for their published, experimental case of slash pine.[40] IS_{t1} is simply the fraction of basal area initially removed.

Figure B1 – Behavior of modeled, loblolly pine stock with and without thinning after 15 years of growth.

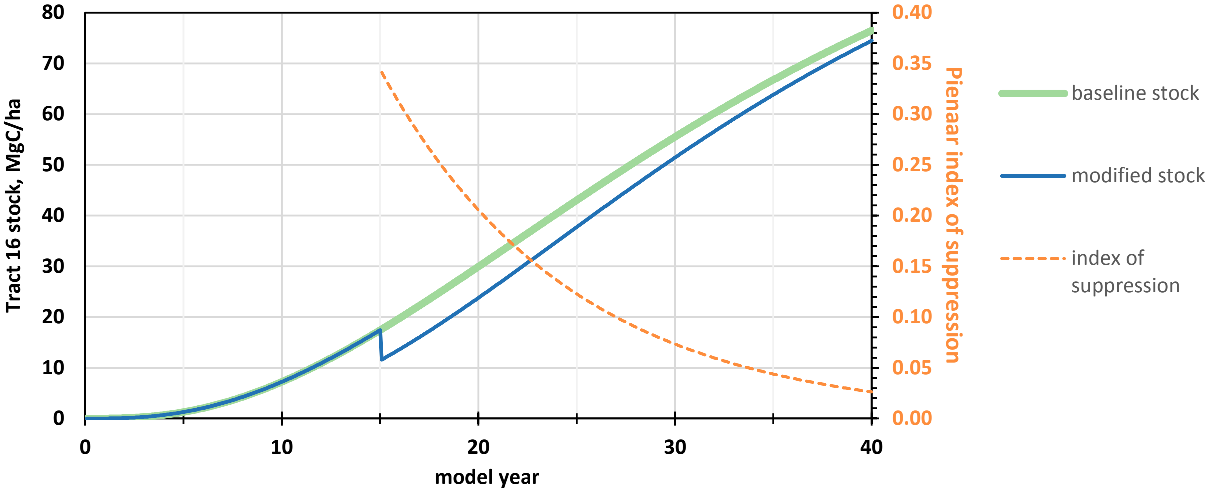
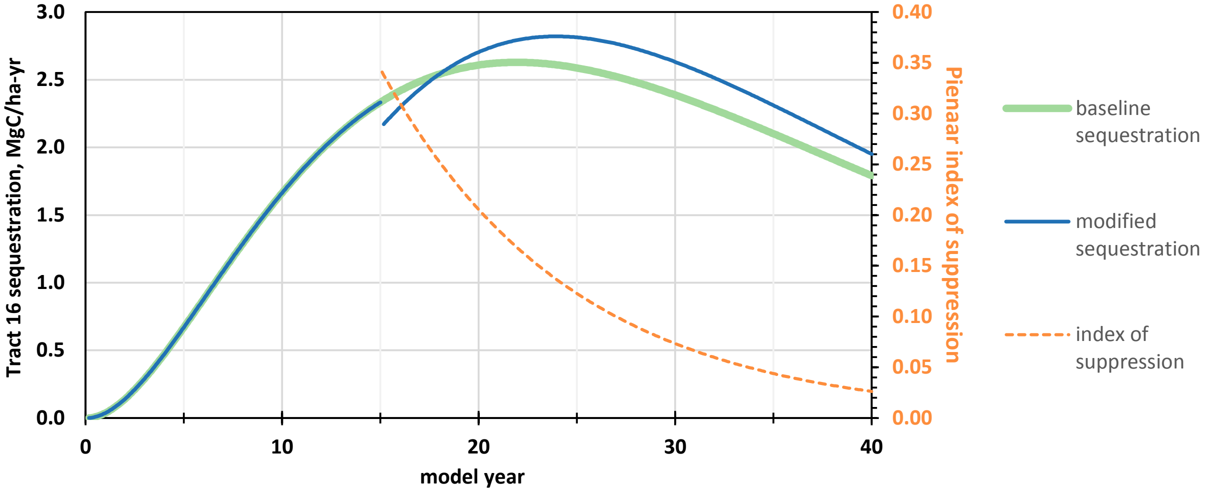


Figure B1 shows modeled, loblolly pine stock from initial planting up to the 40-year time horizon associated with the BECCS model. The green trace is the same stock curve shown in Figure 2. The blue trace shows stock response to a thinning operation that removes 25% of aboveground stock volume (mass) after 15 years of growth. The orange, dashed line is the Pienaar index of suppression, with values shown on the right edge of the chart.

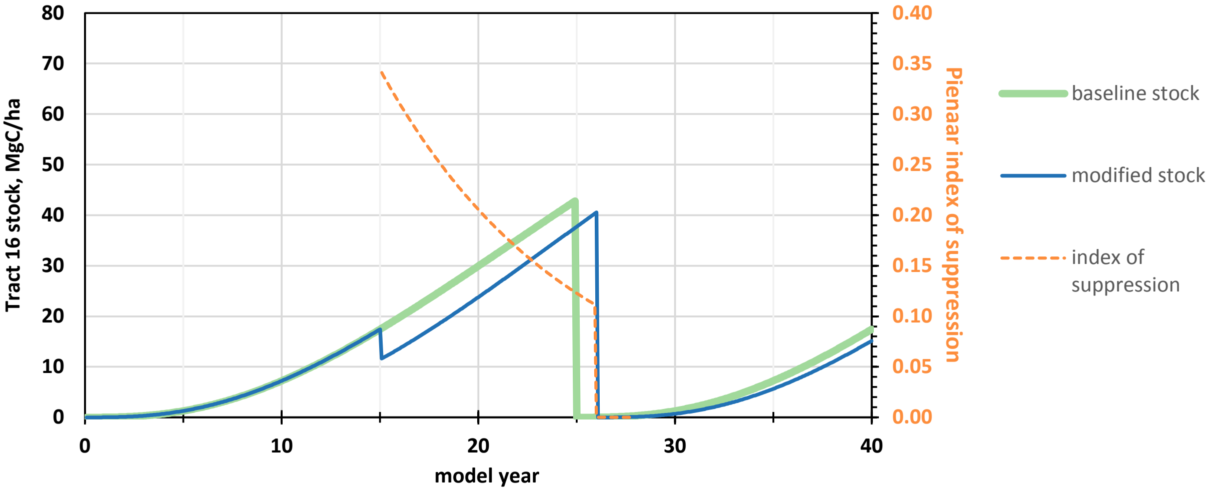
Thinned forest initially loses even more than the 25% of aboveground stock felled, due to natural mortality in response to the shock of thinning – this is the effect observed by Pienaar and driving the value of parameter $\beta_1 = 0.77$. Thereafter, the forest grows more quickly than it would have without thinning, as apparent from the modified stock curve (blue) gradually approaching the reference stock.

Figure B2 – Sequestration response of loblolly pine to thinning after 15 years of growth.



This release effect is manifestly visible if we plot annual increment (sequestration) rather than gross stock (Figure B2). Only a few years after thinning, the annual increment of the thinned forest exceeds that of the reference case and remains that way indefinitely. However, in a practical application the land manager will eventually harvest the thinned stand, so that the stock curve of Figure B1 will actually follow the trajectory shown in Figure B3.

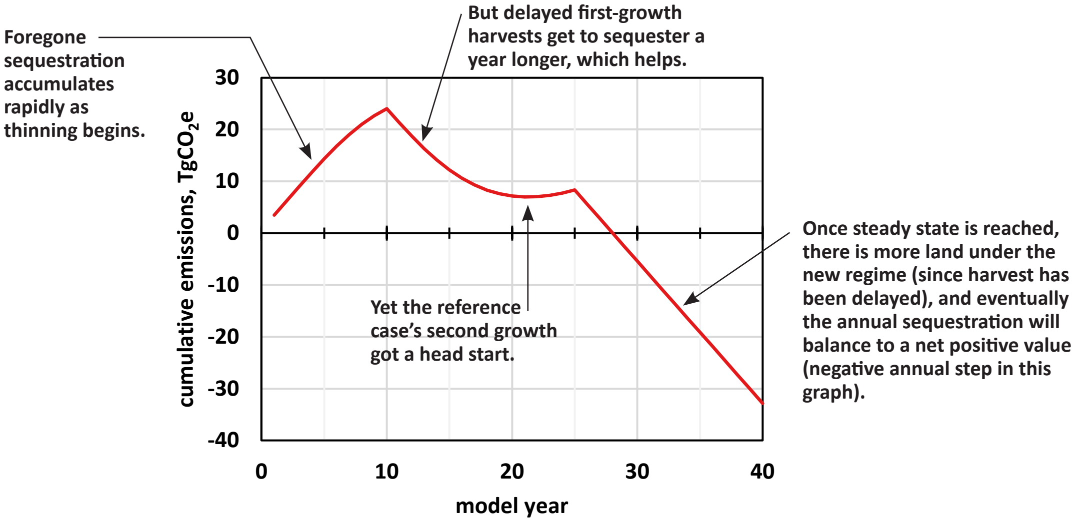
Figure B3 – Land manager's response to thinning.



The land manager does delay harvesting somewhat, in order to retrieve the same quantity of board feet per hectare as they are accustomed to (as would be provided by the reference case). The BECCS model accounts for this, and as shown in Figure B3 with the model parameters set as described in this memo, the land manager needs to delay only one year to achieve sufficient harvest.

A utility-scale BECCS plant will draw biomass from a large number of tracts, each being harvested repeatedly according to the silvicultural rotation length. We simulated this more complex situation for a 25-year reference rotation length, assuming that at each of the 40 years in the analysis, sufficient 25-year-old tracts exist to supply a 500 MW BECCS plant with a heat rate of 10.2 mmBtu/MWh. The computed foregone sequestration in this case is as shown in Figure B4.

Figure B4 – Foregone sequestration in the thinning case.



Foregone sequestration accumulates rapidly as thinning begins.

But delayed first-growth harvests get to sequester a year longer, which helps.

Yet the reference case's second growth got a head start.

Once steady state is reached, there is more land under the new regime (since harvest has been delayed), and eventually the annual sequestration will balance to a net positive value (negative annual step in this graph).

The behavior of foregone sequestration in the thinning case is more complex than in the clearcut case. At first, there is a strong increase in foregone sequestration as forest mass (and hence ability to sequester) is lost. But because the land manager is delaying harvests in response, each tract gets a chance to sequester a bit longer before getting clearcut, an effect which starts showing up in Figure B4 at year 11, the number of years after thinning (at age 15) that the forest is harvested (at age 26 – would have been 25 without thinning). Yet, the reference forest did have a head start on second growth and these two forces oppose each other to produce the bowl-like shape in years 11 through 25.

Finally, steady state is reached at model year 26. Due to the delayed harvest, a slightly larger gross landscape is required to support the new forestry regime, inducing more capacity for sequestration. At this point the annual increment to foregone sequestration becomes negative, and the curve heads linearly downward indefinitely.

Appendix C: Alternative Presentation of Results

Communication of uncaptured biogenic emissions to the public or the policymaking community may require a conceptually simplified approach. This applies especially to the case of foregone sequestration. To provide NRDC with tools for doing so, we offer Tables C1 and C2 below. Relative to Table 6 these offer the following tools for effective communication of results:

Each parameter includes a nominal ("average") value in addition to maximum and minimum;

The clearcut and thinning cases are presented separately, rather than intermingled;

Duration-dependent foregone sequestration is replaced by the concept of foregone sequestration *risk*, a maximum or average value that can be encountered throughout the power plant's lifetime.

Table C1 – Uncaptured biogenic emissions associated with the *Clearcut* BECCS case.

	emissions, kgCO$_2$e/MWh		
emissions source	minimum	nominal	maximum
slash decay	165	296	427
feedstock drying	212	250	287
foregone sequestration risk	87	338	514
capture loss	49	78	107
TOTAL uncaptured biogenic	**513**	**962**	**1,335**

Table C2 – Uncaptured biogenic emissions associated with the *Thinning* BECCS case.

	emissions, kgCO$_2$e/MWh		
emissions source	minimum	nominal	maximum
slash decay	165	296	427
feedstock drying	212	250	287
foregone sequestration risk	0	323	920
capture loss	49	78	107
TOTAL uncaptured biogenic	**426**	**947**	**1,741**

In each of the two cases, the maximum foregone sequestration risk is the highest output-basis foregone sequestration encountered prior to the 40-year model horizon. It represents the strongest contribution to climate forcing that will occur during the plant's lifetime. The nominal foregone sequestration risk is computed as the average value of foregone sequestration between start of operation and reaching sequestration parity. The minimum foregone sequestration risk is the greater of zero, or foregone sequestration at the model horizon. Minimum sequestration risk is nonzero only if sequestration parity would be reached after the model horizon.

In terms of policy goals, attention to the maximum foregone sequestration risk would be consistent with concern for near-term tipping points in the climate system, while attention to the minimum foregone sequestration risk would be consistent with confidence in a climate system that is stable (linearly behaved) through the model's time horizon.

Finally, we recognize that in some instances policymakers might like a sense of the degree to which the energy penalty of CCS is amplifying the biogenic emissions associated with the bioenergy fuel source. For this purpose we offer Tables C3 and C4, in which each of the biogenic emissions sources is reduced by the portion dedicated to supplying carbon capture energy, and in which these portions are presented as a separate sum labeled "CCS efficiency penalty."

Table C3 – Uncaptured biogenic emissions associated with the *Clearcut* BECCS case. With portion dedicated to carbon capture energy segregated.

	emissions, kgCO_2e/MWh		
emissions source	minimum	nominal	maximum
slash decay	128	229	331
feedstock drying	165	194	223
foregone sequestration risk	67	262	398
capture loss	38	61	83
CCS efficiency penalty	115	216	300
TOTAL uncaptured biogenic	**513**	**962**	**1,335**

Table C4 – Uncaptured biogenic emissions associated with the *Thinning* BECCS case. With portion dedicated to carbon capture energy segregated.

	emissions, kgCO_2e/MWh		
emissions source	minimum	nominal	maximum
slash decay	128	229	331
feedstock drying	165	194	223
foregone sequestration risk	0	250	713
capture loss	38	61	83
CCS efficiency penalty	96	213	391
TOTAL uncaptured biogenic	**426**	**947**	**1,741**

In both tables C3 and C4 the carbon capture efficiency penalty is computed based on the nominal value of a 29% increase to plant heat rate.

Appendix D: Issues of Landscape Scale

The BECCS Emissions Simulator computes, as an incidental output, the total quantity of landscape required to support the modeled BECCS plant, depending on which harvest types are being modeled. The values of these outputs are rather stunning in their size and should generate concern, irrespective of the emissions balance. Extreme demands on land use can have negative environmental and economic repercussions, and can even change the sign of the computed emissions balance through indirect land use change.

Electric generating plants that combust solid fuels benefit strongly from efficiency of scale, and are generally built as large as practically possible. As a rule of thumb, coal-fired power plants are in the neighborhood of 1 GW (1000 MW) in size—for example the 248 coal power plants currently operating in the United States have an average nameplate capacity of 960 MW.

As an exercise, we computed the quantity of land required to support a 1 GW biomass plant operating at a real-world 85% capacity factor. A 1 GW biomass plant fueled exclusively by wood pellets from clearcut forestry (again assuming species and site indices typical to the U.S. southeast) would require 1.7 million hectares of dedicated forestland. The same plant fueled exclusively by wood pellets from pre-commercial thinnings would need to be drawing from 16.3 million hectares of host commercial forestland. For reference, the total amount of timberland in the entire U.S. southeast (Florida, Georgia, North Carolina, South Caroline, and Virginia) is 34.7 million hectares, of which 8.8 million hectares are plantation forestry.[41]

So in the case of the U.S. southeast, fueling a single 1 GW plant entirely from clearcut forestry would require an expansion of plantation forestry from 8.8 million hectares to 10.5 million hectares, that is a 19% increase. If instead fueling the plant entirely from pre-commercial thinnings, this would require the cooperation of landowners controlling 16.3 million ha/34.7 million ha = 47% of *all* timberland in the region.

Given that the world consumes some 3,000 average-Gigawatts of electricity, meeting only a small fraction of this with forest-derived biomass induces demands for land that would strain the landscapes of even the largest countries.

ENDNOTES

1 J. Fargione et al., “Land Clearing and the Biofuel Carbon Debt,” *Science* 319, no. 5867 (February 29, 2008): 1235–38, https://doi.org/10.1126/science.1152747.

2 Walter V. Reid, Mariam K. Ali, and Christopher B. Field, “The Future of Bioenergy,” *Global Change Biology* 26, no. 1 (January 2020): 274–86, https://doi.org/10.1111/gcb.14883.

3 Mirjam Röder et al., “Understanding the Timing and Variation of Greenhouse Gas Emissions of Forest Bioenergy Systems,” *Biomass and Bioenergy* 121 (February 2019): 99–114, https://doi.org/10.1016/j.biombioe.2018.12.019.

4 Giuliana Zanchi, Naomi Pena, and Neil Bird, “Is Woody Bioenergy Carbon Neutral? A Comparative Assessment of Emissions from Consumption of Woody Bioenergy and Fossil Fuel,” *GCB Bioenergy* 4, no. 6 (November 2012): 761–72, https://doi.org/10.1111/j.1757-1707.2011.01149.x.

5 Steef V. Hanssen et al., “Wood Pellets, What Else? Greenhouse Gas Parity Times of European Electricity from Wood Pellets Produced in the South-Eastern United States Using Different Softwood Feedstocks,” *GCB Bioenergy* 9, no. 9 (September 2017): 1406–22, https://doi.org/10.1111/gcbb.12426.

6 The BECCS Emission Simulator, Hammerschlag LLC document number NR-030(j). See Appendix A for a methodological description.

7 In this analysis we assume that the fraction of felled biomass destined for slash is equal in clearcut and thinning operations. Future work could potentially recognize a systematic difference between the two, see for example: R.E. Benson and C.M. Johnston, *Logging Residues Under Different Stand and Harvesting Conditions, Rocky Mountains*, USDA Forest Service Research Paper INT (Intermountain Forest & Range Experiment Station, Forest Service, U.S. Department of Agriculture, 1976), https://books.google.com/books?id=qlLxJMDYpdIC.

8 Mohammad Reza Ghaffariyan, “Remaining Slash in Different Harvesting Operation Sites in Australian Plantations,” 2013, 12.

9 Mark S. Ashton and Matthew J. Kelty, *The Practice of Silviculture: Applied Forest Ecology*, 10th edition (Hoboken, NJ: Wiley, 2017), 140.

10 Though the emissions commitment is a constant each year, in cases where the slash is left for decay the physical emissions will follow a more complex curve in early years of the BECCS plant deployment. Eventually, though, the annual slash emissions value will converge to the emissions commitment value.

11 Thomas L. Eberhardt, Joseph Dahlen, and Laurence Schimleck, “Species Comparison of the Physical Properties of Loblolly and Slash Pine Wood and Bark,” *Canadian Journal of Forest Research* 47, no. 11 (November 2017): 1495–1505, https://doi.org/10.1139/cjfr-2017-0091.

12 In forestry, moisture content of a sample is defined as the mass of the water in the sample, divided by the dry mass of the sample. Since most green wood can easily hold its own mass in water, this value may exceed 100% under ordinary field conditions.

13 Augusto Uasuf, “Economic and Environmental Assessment of an International Wood Pellets Supply Chain: A Case Study of Wood Pellets Export from Northeast Argentina to Europe,” 2010.

14 Hanssen et al., “Wood Pellets, What Else?”

15 Uasuf, “Economic and Environmental Assessment of an International Wood Pellets Supply Chain: A Case Study of Wood Pellets Export from Northeast Argentina to Europe.”

16 Gerold Thek and Ingwald Obernberger, “Wood Pellet Production Costs under Austrian and in Comparison to Swedish Framework Conditions,” *Biomass and Bioenergy* 27, no. 6 (December 2004): 671–93, https://doi.org/10.1016/j.biombioe.2003.07.007.

17 43.98 kJ/mol at 25 degrees C, see William M. Haynes and David R. Lide, eds., *CRC Handbook of Chemistry and Physics: A Ready-Reference Book of Chemical and Physical Data*, 94. ed., 2013–2014 (Boca Raton, Fla.: CRC Press, 2013).

18 Thek and Obernberger, “Wood Pellet Production Costs under Austrian and in Comparison to Swedish Framework Conditions.”

19 See Appendix A for sources of these parameters.

20 A 25-year rotation was chosen as typical for southeastern United States loblolly plantations, for consistency with the sample growth curve.

21 HHV-basis, after carbon capture but before carbon sequestration. See discussion of power plant efficiency and parasitic load at page 11.

22 Yuan Wang et al., “A Review of Post-Combustion CO2 Capture Technologies from Coal-Fired Power Plants,” *Energy Procedia* 114 (July 2017): 650–65, https://doi.org/10.1016/j.egypro.2017.03.1209. (See additional citations within.)

23 e.g., International CCS Knowledge Center, “The Shand CCS Feasibility Study - Public Report” (International CCS Knowledge Center, November 2018).

24 All heat rates and efficiencies discussed in this report are on a higher heating value (HHV) basis. Efficiencies computed on an HHV basis will appear lower than efficiencies computed on an LHV basis, which are equally common in the literature.

25 U.S. Energy Information, *Electric Power Annual*, Table 8.1, Release date 2021-02-22.

26 Richard J Campbell, “Increasing the Efficiency of Existing Coal-Fired Power Plants,” CRS Report for Congress (Congressional Research Service, December 20, 2013). p.15, Table 2.

27 Massachusetts Institute of Technology, “The Future of Coal: Options for a Carbon-Constrained World.” (Boston MA: Massachusetts Institue of Technology, 2007), http://web.mit.edu/coal/The_Future_of_Coal.pdf p.19 Table 3.1.

28 International CCS Knowledge Center, “The Shand CCS Feasibility Study - Public Report,” 63.

29 Wang et al., “A Review of Post-Combustion CO2 Capture Technologies from Coal-Fired Power Plants,” 658–60.

30 Jochen Oexmann et al., “Optimized Integration of Post-Combustion CO2 Capture Process in Greenfield Power Plants” (12th International Post Combustion Capture Network Meeting, Regina, CND, 2009), 21.

31 “IPCC Special Report on Carbon Dioxide Capture and Storage,” IPCC Special Report (Cambridge University Press, 2005), 164.

32 Peter Folger, “Carbon Capture: A Technology Assessment,” CRS Report for Congress (Congressional Research Service, November 5, 2013), 16.

33 Branimir Tramošljika et al., "Advanced Ultra-Supercritical Coal-Fired Power Plant with Post-Combustion Carbon Capture: Analysis of Electricity Penalty and CO2 Emission Reduction," *Sustainability* 13, no. 2 (January 15, 2021): 17–18, https://doi.org/10.3390/su13020801.

34 The 100-year global warming potential (GWP) of methane is 28, per the IPCC Fifth Assessment Report. GWP is computed on a mass basis, but each carbon atom that decays to a CH_4 molecule generates only 36% as much mass as when it decays to the heavier CO_2 molecule.

35 U.S. EPA, "EGRID Summary Tables 2018" (U.S. EPA, March 9, 2020), https://www.epa.gov/egrid/download-data.

36 For harvest type HERB, forest growth still needs to be modeled to represent the REF case, in which the cropland is afforested instead.

37 James E. Smith et al., "Methods for Calculating Forest Ecosystem and Harvested Carbon with Standard Estimates for Forest Types of the United States," General Technical Report (Forest Service, United States Department of Agriculture (USDA), 2006), 94, http://www.actrees.org/files/Research/ne_gtr343.pdf.

38 H Hasenauer, H E Burkhart, and R L Amateis, "Basal Area Development in Thinned and Unthinned Loblolly Pine Plantations" 27 (1997): 7.

39 L V Pienaar, "An Approximation of Basal Area Growth after Thinning Based on Growth in Unthinned Plantations," *Forest Science* 25, no. 2 (1979): 223–32.

40 *IS* per Pienaar is based on basal area, whereas the BECCS simulator estimates forest mass, which is proportional to volume rather than area. This has no impact on Pienaar's equation when all trees in the thinned forest are identical. This is a reasonable, simplifying assumption for even-aged plantation forests, but future refinement of this methodology may account for different responses on a volume vs. basal area basis when thinning is from below.

41 Sonja N. Oswalt et al., "Forest Resources of the United States, 2017: A Technical Document Supporting the Forest Service 2020 RPA Assessment" (Washington, DC: U.S. Department of Agriculture, Forest Service, March 2019), https://www.fs.usda.gov/treesearch/pubs/57903.